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DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES
JOHN W. FINCH, DIRECTOR

INFORMATION CIRCULAR

TUNGSTEN - PART I

BY

WILLIAM O. VANDERBURG

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By William O. Vanderburg [2]

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INTRODUCTION

This circular is one of two papers on the tungsten industry in the United States and contains general information on the subject. The second paper which will be issued in the near future deals with the methods and costs of mining and milling tungsten ores. These two papers are abstracts from the general bulletin on tungsten which will be issued at some future time.

Modern civilization and progress depend largely on tools wherewith the forces of nature are brought under control and directed toward human comfort. These tools are made chiefly from metals derived from the earth's crust. During the present century powerful tools have been made available through the development of ferrous and nonferrous alloys containing such elements as molybdenum, vanadium, titanium, tantalum, and tungsten, which were little used before 1900. One of the most important of these so-called rare elements is tungsten; its use in alloys for high-speed cutting tools is partly responsible for the era of mass production. So widespread has the use of alloys become that the period may be termed an "Alloy Age".

Tungsten is recognized as an essential ingredient of the best high-speed cutting tools. The major part of the 4,300 tons of tungsten concentrate containing 60 percent tungsten trioxide (WO_3), consumed annually in the United States under normal conditions, is used in the manufacture of such tools.

HISTORY

In 1747, Wallerius selected the name tenn-spat (heavy spar or heavy mineral) for a new mineral species from Bohemia believed to contain tin.[3] In 1781, K. W. Scheele, the celebrated Swedish chemist, examined a specimen of Wallerius tenn-spat (Swedish, tung-sten) and demonstrated that the mineral contained a peculiar acid united to lime as a base. This acid he called tungstic acid. In the same year T. Bergman stated that this acid was an oxide of a new element, tungsten. From 1783 to 1786 the d'Elhuyar brothers, Juan, Jose, and Fausto, Spanish chemists, showed that the same acid discovered by Scheele is contained in the mineral wolframite. They also succeeded in producing metallic tungsten from the acid.[4] The term "wolframite" was applied to tungsten minerals long before their nature was understood.

In 1801, a short note in Nicholson's journal states that Guyton had melted tungsten; but it was brittle and probably of use only in alloys, for making fixed colors, or for fixing vegetable colors - three of its present uses.[5]

3/ Levy, S. I., The Rare Earths: Edward Arnold, London, 1915, p. 31.
4/ Roscoe, H. E., and Schorlemmer, C. A., A Treatise on Chemistry: Vol. 2, 1913, pp. 1082-1083.
5/ Thorpe, Sir Edward, A Dictionary of Applied Chemistry: Vol. 5, 1913, p. 563.

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As early as 1855,[6] Jacobs and Koeller of Austria used tungsten as a constituent of alloy steel. They obtained patents in France for its production.

Patents were issued to Oxland in England in 1847[7] for the manufacture of sodium tungstate, tungstic acid, and metallic tungsten from wolfram-tin ores. These were followed by a patent issued in 1857 for the production of certain alloys with iron and steel, nickel, and other elements.

Probably the first useful alloy steel containing tungsten was Mushet's self-hardening tungsten tool steel, patented in 1868. This steel, now obsolete, contained about 6 percent tungsten and 2 percent manganese. In regard to the use of tungsten for hardening steel, the old Damascus steel, long celebrated for its retention of temper, has been found to contain both tungsten and chromium,[8] although not intentionally added.

The real birthdate of the tungsten tool-steel industry was 1898, when F. W. Taylor, in collaboration with Maunsel White, discovered a steel that could be used to cut at high speed. Taylor-White steels manufactured at the works of the Bethlehem Steel Co. were exhibited at the Paris Exposition in 1900 and created a great sensation among those interested in working metals. These tools could be used above temperatures that would ruin any carbon steel. White stated[9] that a young man in the Bethlehem shop in 1900 lighted a cigarette with a chip newly cut with Taylor-White steel, a statement almost unbelievable at that time.

In 1903 Hadfield published the results of his studies of the properties of tungsten steels. These extensive investigations contributed largely to the demand for tungsten tool steels.

In addition to cutting at higher speeds, tungsten-steel tools were found to be capable of taking heavier cuts, which increased the stresses on the machines. To take full advantage of the heavier as well as the more rapid cuts machines were redesigned to provide the greater strength required. The resulting economies effected all over the world were enormous, and the new tungsten-steel tools were the dominant factor in the new era of mass production of machine-tool products.

The extremely high melting point of tungsten suggested its use for electric-lamp filaments, but at the time of its introduction as a lamp filament (1904) it was known only as a powdery, hard, brittle metal which it was impossible to render coherent and ductile. Numerous processes were invented and patented wherein the filaments were made with powdered tungsten; these were used with more or less success until drawn tungsten wire for

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6/ Gurlt, Adolph, On a Remarkable Deposit of Wolfram Ore in the United States: Trans. Am. Inst. Min. Eng., vol. 22, 1893, p. 236.
7/ Roscoe, H. E. and Schorlemmer, C. A., work cited.
8/ Thorpe, Sir Edward, work cited.
9/ Hibbard, Henry D., Manufacture and Uses of Alloy Steels: Bull. 100, Bureau of Mines, 1916, p. 54.

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incandescent lamp filaments was developed by the General Electric Co. The ductile tungsten-lamp filament was introduced in 1907. The greater efficiency of the tungsten electric lamp over the types of lamps formerly used resulted in the saving of millions of dollars annually.

Within the last few years a new tungsten compound has been developed which bids fair to supersede the former high-speed tool steels in cutting efficiency. This new material is known as cemented tungsten carbide; cobalt is used as the cementing agent. The material was first developed in Germany; Baumhauer and Schröter are given the major credit for its development. The patents are held by Fried. Krupp Aktiengesellschaft, Essen, Germany; in this country licensees manufacture it under the trade names carboloy, firthite, firthalloy, dimondite. Tungsten carbide is the hardest artificial substance known, exceeding the sapphire and approaching the diamond in hardness. Properly made, tungsten-carbide tools will cut chilled castings, manganese steel, porcelain, mycalex (fine mica in lead borate), ivory, quartz, and other substances not readily cut with other tools.

Few elements have shown greater development in so short a time as tungsten. Before the present century tungsten was more of a scientific curiosity than a metal of commercial importance, but with introduction of Taylor-White tool steel it was lifted out of the category of rare metals to a position where it has become one of the key metals of our present economic structure.

TUNGSTEN MINERALS

Tungsten is never found in nature in the metallic state. It is an acid-forming element and therefore does not act as a true metal in its compounds. The economic tungsten minerals are tungstates, in which the tungsten is combined with oxides of calcium, iron, and manganese. Although a number of tungstic acids have been prepared artificially salts of only one acid have been found in nature, namely, those of the normal tungstic acid (H_2WO_4). Tungsten has been identified in a number of minerals as impurities, but only 12 distinct species of minerals containing tungsten are known. In virtually all of its minerals tungsten is one of the chief constituents, the two exceptions being powellite and chillagite.

Table 1 lists the known tungsten minerals and gives their theoretical composition and the percentage of tungsten each mineral contains:

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TABLE 1. - Tungsten minerals

Mineral	Composition	Tungsten, percent[1/]
Scheelite	Calcium tungstate ($CaWO_4$)	63.9
Ferberite	Iron tungstate ($FeWO_4$)	60.6
Wolframite	Iron-manganese tungstate ($(Fe,Mn)\ WO_4$)	60.6-60.7
Hübnerite	Manganese tungstate ($MnWO_4$)	60.7
Powellite	Calcium-tungstomolybdate ($Ca\ (MoW)\ C_4$)	-
Chillagite	Lead tungstate-lead molybdate ($3PbWO_4.5PbMO_4$)	17.2
Stolzite	Lead tungstate ($PbWO_4$)	40.4
Raspite	Lead tungstate ($PbWO_4$)	40.4
Cuprotungstite	Hydrous copper tungstate ($CuWO_4.2H_2O$)	52.9
Tungstite	Hydrous tungsten trioxide ($WO_3.H_2O$)	73.6
Tungstenite	Tungsten sulphide (WS_2)	74.6
Ferritungstite	Hydrous iron-tungsten oxide ($Fe_2O_3.WO_3.6H_2O$)	41.5

1/ Based on theoretical composition.

Stolzite and raspite differ only in crystal form, the former being tetragonal and the latter monoclinic.

Reinite ($FeWO_4$) as given by Dana[10/] is a separate species, but it is now regarded as ferberite pseudomorphous after scheelite.

Cuproscheelite, according to Dana, is a tungstate of copper and calcium $(Ca,Cu)WO_4$; it may be scheelite partly altered to cuprotungstite in which the calcium has not been wholly replaced by copper.

Meymacite, named by Carnot, is probably the same as tungstite.

The term "megabasite" has been used in early reference on tungsten as a synonym of hübnerite.

Of the above list only the first four minerals - scheelite, ferberite, wolframite, and hübnerite - are found in large enough quantities to be economically important as ores of tungsten. The others are to be considered in the light of interesting mineralogical occurrences. Besides these Dana's System of Mineralogy mentions that small amounts of tungsten are contained in the tantalum-columbium minerals, but the information concerning them is so incomplete that their existence as definite mineral species can not be considered authentic.

10/ Dana, J. D., and Dana, E. S., A System of Mineralogy: New York, 6th ed., 1911, p. 991

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CHARACTERISTICS OF ECONOMIC TUNGSTEN MINERALS

The physical and chemical properties of the four principal tungsten minerals are given in table 2.

TABLE 2. - Physical and chemical properties of economic tungsten minerals

Mineral	Ferberite	Wolframite	Hübnerite	Scheelite
Composition (pure)	$FeWO_4$	$(Fe,Mn)WO_4$	$MnWO_4$	$CaWO_4$
Per cent WO_3 and W	76.3; 60.6	76.5; 51.3	76.6; 60.7	80.6; 63.9
Crystallization	Monoclinic.	Monoclinic.	Monoclinic.	Tetragonal.
Cleavage	Perfect in 1 direction.	Perfect in 1 direction.	Perfect in 1 direction.	Good in 4 directions.
Specific gravity	7.5	7.1-7.5	7.2-7.3	5.4-6.1
Color	Black	Dark gray to black.	Reddish brown to black.	Pale yellow, brown, commonly white.
Tenacity	Very brittle.	Very brittle.	Very brittle.	Very brittle.
Luster	Submetallic to metallic.	Submetallic to metallic.	Submetallic to adamantine.	Vitreous to resinous.
Fracture	Uneven.	Uneven.	Uneven.	Uneven.
Hardness	5	5-5.5	5	4.5-5
Magnetism	Sometimes feebly magnetic.	Slightly magnetic.	-	Nonmagnetic.
Streak	Dark brown to nearly black.	Dark brown to black.	Brownish red to greenish yellow.	White
Diaphaneity	Opaque to weakly translucent in cleavage plates.	Opaque.	Opaque to translucent.	Transparent to translucent.
Common form of occurrence	Well-defined crystals, massive cryptocrystalline.	Irregular masses.	Radiating groups of thin-bladed crystals.	Massive and small grains.

The three minerals ferberite, wolframite, and hübnerite form a continuous series of iron-manganese tungstates, of which ferberite is the member at the iron end and hübnerite is the member at the manganese end. The iron and manganese contents of the wolframite series are so variable that the minerals cannot be distinguished without chemical analyses. No specimen of ferberite free from manganese or hübnerite free from iron has been found in nature. Since the wolframites form a complete series with an indefinite number of

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members any classification of the minerals into ferberite, wolframite, and hubnerite must necessarily be arbitrary. The following definitions proposed by Hess[11] are generally accepted:

Ferberite. A monoclinic iron tungstate having when pure the composition $FeWO_4$. It may contain not more than 20 percent of the hubnerite molecule $MnWO_4$.

Wolframite. A monoclinic mineral containing the ferberite molecule ($FeWO_4$) and the hubnerite molecule ($MnWO_4$) in all proportions between 20 percent $FeWO_4$ and 80 percent $MnWO_4$ and 80 percent $FeWO_4$ and 20 percent $MnWO_4$.

Hubnerite. A moloclinic manganese tungstate having when pure the composition $MnWO_4$. It may contain not more than 20 percent of the ferberite molecule $FeWO_4$.

The wolframites are metallic in appearance, while scheelite looks like stone.

The economic tungsten minerals are characterized by high specific gravity,[12] ranging from 5.4 (scheelite) to 7.5 (wolframite). (See table 2.) The tungsten minerals are 2 to nearly 3 times as heavy as quartz, which has a specific gravity of 2.6. This property of the tungsten minerals is utilized in making a separation between quartz, calcite, and other minerals of lower specific gravity when ores are concentrated by gravity methods.

Because of their similarity in chemical composition and the fact that the atomic weights of iron and manganese are almost the same (Fe, 55.84; Mn, 54.93), the wolframites contain almost the same percentages of tungsten trioxide.

Each of the wolframite series of minerals has a perfect plane of parting (cleavage) in one direction. Scheelite has eight planes of parting, four of which are pronounced and four which are not pronounced.

The principal tungsten minerals have a hardness of about 5, as measured on the Mohs scale of hardness;[13] they are easily scratched with the blade of a good pocket knife, which has a hardness of about 5 1/2.

The streak of a mineral (the color of its fine powder) usually is obtained by rubbing the mineral on a piece of unglazed porcelain and brushing off the excess, or it may be obtained less satisfactorily by pulverizing a

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11/ Hess, Frank L., and Schaller, Waldemar T., Colorado Ferberite and the Wolframite Series: U. S. Geol. Survey Bull. 583, 1914, pp. 37-38.

12/ The specific gravity of a substance is its weight compared with that of an equal bulk of water at the temperature of greatest density (4°C. or 39.29° F.).

13/ Mohs' scale of hardness, which is used for minerals, is: 1, Talc; 2, gypsum; 3, calcite; 4, fluorite; 5, apatite; 6, feldspar; 7, quartz; 8, topaz; 9, sapphire; 10, diamond.

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fragment of the mineral or by scratching the mineral with a knife or file. The streak of the wolframites ranges from black in wolframite through brown to brownish red in hübnerite. The streak of scheelite is white.

OCCURRENCE

Tungsten is rated as the thirty-eighth[14/] element in the order of abundance in the earth's crust; it is less abundant than tin or silver, the thirty-third and thirty-seventh elements, respectively, but is more abundant than gold, the forty-first element. Tungsten is distributed very unequally over the earth as a whole; it is distributed more widely than tin, with which it is commonly associated, but less widely than gold. The chief tungsten-producing districts of the world follow the volcanic chain which skirts the Pacific Ocean. Although the deposits are not always near the shore they are somewhere in the mountain ranges that parallel it. From 1905 until 1930, 88.4 percent of the total world production of tungsten concentrates came from countries bordering the shores of the Pacific. Of this percentage the west coasts of North and South America produced 25.2 percent and the east coast of Asia and Oceania (Australia and New Zealand) 63.2 percent. The only large producing area not close to the Pacific is that of the Iberian Peninsula, including Portugal and part of Spain. Of the 11.6 percent of the world production of tungsten concentrates from countries not bordering the Pacific, the Iberian district produced 7.8 percent.

Tungsten deposits are represented in almost every type of ore deposit; these include placers, veins, contact-metamorphic deposits, replacement deposits, pegmatites, and segregation deposits. Viewed in the light of past production placers have been the most important source of tungsten minerals.

Tungsten deposits, like tin and molybdenum deposits, are virtually always associated with siliceous igneous rocks, especially granites or acid pegmatites; in this respect they differ from any other minerals. The converse of this statement is not true, however, as large areas of granitic rocks all over the world are not associated with tungsten deposits. Most of the tungsten deposits in place lie wholly within or at the margins of the acid igneous rocks; some, however, lie within sedimentary rocks, such as slates and shales, or metamorphic rocks, such as schists. Where the tungsten deposits lie within the latter rocks and siliceous rocks are not in evidence in the immediate vicinity the underlying granitic rock is not far distant.

PRODUCTION AND CONSUMPTION

The United States is one of the largest consumers of tungsten. Although it also ranks as one of the largest producers it has had to supplement domestic supply by importation, principally from China. Before 1900 tungsten ores were derived chiefly from mines in England, Austria, Hungary, Germany, and Australia. The United States became a factor in tungsten production about 1900.

14/ Washington, H. S., Jour. Franklin Inst., vol. 190, 1920, p. 77.

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TABLE 3. - World production of tungsten ore, 1905-32, in metric tons of concentrates containing 60 percent WO_3 1/

Country	1905-25	1926	1927	1928	1929	1930	1931	1932
Asia:								
Japan	5,044	19	49	54	61	81	(2)	(2)
Chosen (Korea)	2,857	-	5	161	15	13	(2)	(2)
China	40,056	7,989	5,666	8,283	9,978	9,454	7,492	2,249
Tonkin (Indo-China)	3,466	92	213	175	198	220	248	(2)
Burma and Shan States	32,392	1,634	1,277	843	1,489	2,699	2,474	(2)
Siam	3,441	10	8	-	62	7	12	(2)
Unfederated Malay States	4,557	234	170	139	157	178	241	(2)
Federated Malay States	4,659	99	22	5	356	1,054	462	378
Netherland East Indies	598	9	22	8	10	15	1	(2)
India (excluding Burma)	186	-	-	-	-	-	-	-
Oceania:								
Australia 3/	18,879	99	179	238	223	224	-	-
New Zealand	2,711	15	15	6	39	21	6	(2)
South America:								
Argentina	8,657	11	10	24	63	98	20	(2)
Bolivia	17,793	109	79	29	1,630	888	410	1,000
Peru	2,673	-	-	-	-	-	-	-
North America:								
Canada	116	-	-	-	-	-	-	-
Mexico	1,068	-	-	-	11	28	(2)	(2)
United States	31,279	1,254	1,056	1,096	753	637	1,274	359
Europe:								
Sweden	38	-	-	-	-	-	-	-
England	4,239	20	12	96	27	153	121	(2)
France	1,688	26	22	5	1	-	-	(2)
Portugal	15,476	358	174	151	358	499	274	(2)
Spain	4,116	123	164	193	257	254	135	(2)
Italy	88	-	-	-	-	-	-	-
Austria	574	-	-	-	-	-	-	-
Germany	2,034	-	-	-	1	-	-	(2)
Czechoslavakia	335	86	78	73	75	74	17	(2)
Russia	199	22	32	53	(2)	(2)	(2)	(2)
Africa:								
Southern Rhodesia	192	-	33	15	28	38	24	14
Union of South Africa	322	-	-	-	-	-	2	-
Nigeria	32	-	-	-	-	-	-	-
All other Countries	43	-	-	(4)	-	-	-	-

1/ Data from the U. S. Geological Survey and U. S. Bureau of Mines.
2/ Data not available.
3/ Includes Tasmania.
4/ Ethiopia reports an experimental production of 100 tons of tungsten ore in 1928; WO_3 content not stated.

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From 1905 to 1931 the total world production has been about 279,400 metric tons of concentrates containing the equivalent of 60 percent WO_3. Out of this production China produced approximately 32 percent, Burma and Shan States 14.3 percent, United States 13.5 percent, Bolivia and Australia each 7 percent, and Portugal 6 percent. Table 3 shows the world production of tungsten from 1905 to 1932.15/

Figure 1 shows the world production, United States production and apparent consumption of tungsten from 1905 to 1932. In the figure figures on consumption and production are reduced to equivalent short tons of concentrates containing 60 percent WO_3.

The international balance sheet of tungsten covering data from 1925 to 1926 is estimated to be approximately as shown in table 4.16/

TABLE 4. - International balance sheet of tungsten

Supply	Metric tons	Percent of total	Demand	Metric tons	Percent of total
China	8,020	63.4	United States.	3,900	30.8
Burma	1,610	12.7	Germany	3,850	30.5
United States	980	7.8	United Kingdom	1,700	13.4
Bolivia	470	3.7	France	3,000	23.7
Unfederated Malay States	170	1.3	Japan	200	1.6
Portugal	230	1.8			
Australia	200	1.6			
Tonkin	190	1.5	Total	12,650	100.0
Spain	140	1.1			
Federated Malay States	260	2.1			
All others	380	3.0			
	12,650	100.0			

15/ Data from annual Mineral Resources of the United States Geological Survey 1906-23) and the United States Bureau of Mines (1924-31) and from the Minerals Yearbook of the Bureau of Mines (1932).

16/ Hess, Frank L., Tungsten: Mineral Resources of United States, Bureau of Mines, 1930, part I, 1932, pp. 179-207.

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TUNGSTEN DEPOSITS IN THE UNITED STATES

The known tungsten deposits in the United States lie mainly in the area between the Rocky and Sierra Nevada Mountains. Thirteen States have at some time in the past produced tungsten concentrates; in the approximate order of their importance as producers they are: Colorado, California, Nevada, Arizona, South Dakota, Washington, Montana, New Mexico, Utah, Idaho, Connecticut, Missouri, and Oregon. The bulk of the production has been derived largely from the first three States. In addition to the above States tungsten minerals have been reported from several others, but these occurrences are of mineralogical rather than actual or potential economic importance.

Arizona.- Virtually all of the tungsten deposits of Arizona are vein deposits, several of which are associated with placers. Fifteen widely scattered deposits occur in various parts of the State; most of these have been worked at some time during the past 15 years, but production from the individual deposits has been small and rather sporadic. In recent years the two most important properties in the State have been the Boriana Mines Co., which operates a consolidation of properties about 16 miles northeast of Yucca, and the Tungsten Alloys Corporation, which owns property in the Las Guigas Mountains 65 miles south of Tucson.

California.- The most important deposits in California are in San Bernardino, Inyo, and Kern Counties. Five other counties in the State contain tungsten deposits. The chief producing area has been the Atolia district, with an output of tungsten concentrates valued at $12,000,000. In this district the ore mineral is scheelite, which occurs in veins and placers. Important contact-metamorphic deposits were developed near Bishop and at Pine Creek, Inyo County. Several properties built large mills between 1916 and 1918, but as the demand and price of tungsten concentrates dropped considerably at the close of the war the plants were forced to close down. The ores of the Bishop and Pine Creek districts are of low grade. Other districts in the State have produced small amounts of tungsten concentrates; but because of adverse conditions, such as lack of cheap transportation, long distance from power, and scarcity of water and timber in the immediate vicinity of the deposits, many have not been prospected or developed thoroughly.

Colorado.- The production of tungsten concentrates in Colorado has been derived almost entirely from the ferberite vein and placer deposits of the Boulder field, which is about 12 miles long and several miles wide. This field contains the largest deposits of ferberite in the world; these were worked intensively during the war period. At that time there were 21 concentrators in the district. In recent years the Wolf Tongue Mining Co. has been the largest and most consistent producer in the district.

The tungsten deposits in other parts of the State have not been important producers.

Connecticut.- A small deposit of scheelite and wolframite ore has been worked at Long Hill 8 miles south of Trumbull, Conn. The mill at this property burned in 1916, and no production has been made since.

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Idaho.- Tungsten deposits have been found in six widely scattered districts in Idaho. The deposits that have been worked are in Shoshone County, adjoining the gold camp of Murray, and in the Patterson Creek district, Lemhi County. In the Murray district the Golden Chest and Golden Winnie Mines have produced small amounts of scheelite, which occurs with gold. In the Patterson or Blue Wing district the Ima Mine has produced a small amount of hübnerite, which is associated with tetrahedrite and copper. In recent years the production from the tungsten properties in the State has been negligible.

Missouri.- The Old Einstein mine in the granitic area of Madison County 12 miles west of Fredericktown has produced small quantities of hübnerite. This property was first opened in 1877 for argentiferous galena with which the hübnerite is associated.

Montana.- The Jardine Mining Co. at Jardine, Mont., has made intermittent shipments of scheelite concentrates within the last few years. Here the scheelite is associated with gold and arsenopyrite in quartz veins. Both the gold and arsenopyrite are more important economically than the scheelite. Several other deposits of tungsten ores occur within the State but thus far have been only small producers.

Nevada.- Most of the tungsten concentrates produced in the United States with the last 5 years have been derived from the contact-metamorphic deposits in the Eugene Mountains 7 miles northwest of Mill City, Pershing County, Nev. These deposits are owned by the Nevada Massachusetts Co., Inc. The Silver Dyke mine in the Silver Star district, Mineral County, has also been a major producer of scheelite concentrates; it is also owned by the Nevada Massachusetts Co., Inc. A new mill was erected on this property in 1930. Another potential producer of scheelite in Nevada is the Tungsten Production Co. in the Nightingale district, Pershing County. A concentrator was built on this property in 1930 to treat the scheelite ore, which occurs in contact-metamorphic deposits.

In the past a considerable production of tungsten concentrates has been made from the vein and placer deposits in the Snake Range in the eastern part of the State. Since the World War, however, Snake Range deposits have been inactive.

The tungsten vein deposits scattered throughout the State have been worked intermittently on a small scale. Probably not more than 25 percent of the contact-metamorphic deposits have been prospected or developed to any extent because of scarcity of water and timber in the vicinity of the properties, long distance from hydroelectric power lines, and recent discovery. Virtually all the contact-metamorphic tungsten deposits of Nevada and California were discovered between 1916 and 1918. These deposits constitute the largest reserve of tungsten ores in the United States.

New Mexico.- Tungsten ores have been found in four districts of the State. The small quantities of tungsten concentrates produced were mainly byproducts from the mining of gold, silver, and copper ores.

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Oregon.- During the World War a small quantity of concentrates was produced from the gold-scheelite veins in the Cliff mine, Virtue district. There is no record of any production of tungsten from Oregon in recent years.

South Dakota.- South Dakota has produced tungsten concentrates valued at $1,300,000, largely from the replacement deposits in the Lead-Deadwood area. The principal mines in this area have been the Wasp No. 2 and the Homestake. Production from this State since 1928 has been negligible. The pegmatites of the Harney Peak and Tinton districts have yielded small quantities of tungsten concentrates.

Utah.- Two deposits of tungsten ores of economic importance occur in Utah, one in the Grouse Creek Mountains and the other in the Clifton district, Tooele County. Neither has been a large producer.

Washington.- Seven tungsten deposits occur in Washington, four of which are in Stevens County. The most important tungsten property in the State has been the old Germania mine, now owned by the Tungsten Producers, Inc., in the Deer Trail district; the economic tungsten minerals are wolframite and scheelite, which occur in quartz veins. A new mill was erected on this property in 1931. The Tungsten Mines, Inc., and the Northwest Tungsten Co., Inc., have been developing their properties within the last 3 years.

TECHNOLOGY OF TUNGSTEN ORES

The mining of tungsten ores in the United States involves no factors which are not inherent in mining similar types of ore deposits of the other metals. In mining narrow deposits of tungsten ores where the enclosing rocks are structurally strong, the open-stope or shrinkage-stope methods of mining are employed; where the wall rocks are weak the cut-and-fill system is used. In mining disseminated ores where the deposits occur in large, irregular masses, the glory-hole system of mining has been employed, as at the Pine Creek and Round Valley mines near Bishop, Inyo County, Calif.

Placer tungsten deposits in the United States generally are worked on a small scale by hand methods; the one exception is the placer deposit at Atolia, San Bernardino County, California, which has been worked by power shovel.

At present the concentration of tungsten ores in the United States depends basically on wet gravity methods, although recent research work by the Bureau of Mines[17/] has demonstrated that some tungsten ores are amenable to the flotation process.

In deposits where the tungsten mineral occurs in coarse form the ore is crushed and then concentrated by jigs followed by further crushing and the use of tables for recovering the finer particles. When the tungsten mineral occurs in fine particles, stage-crushing by rolls is followed by classification before

17/ Coghill, Will H. and Clemmer, J. Bruce, Soap Flotation of the Nonsulphides: Am. Inst. Min. and Met. Eng., Tech. Pub. 445, 1932, pp. 13-16.

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table treatment. If pyrite, garnet, epidote, or chalcopyrite is present in the bulk table concentrate magnetic separators are used to remove these minerals to produce a cleaner product.

In concentrating tungsten ores by gravity methods the main object is to remove the tungsten mineral in as coarse a form as possible to avoid excessive loss of the mineral in the slimes. The economic tungsten minerals are brittle and slime readily, therefore rolls generally are employed for secondary crushing in stages, in preference to stamp or ball mills.

CONVERSION OF CONCENTRATES

Steel Making

In the manufacture of tungsten steel the concentrates may be introduced directly into the steel bath; because of the greater purity of the concentrates this method is increasing in use. As the calcium in scheelite slags more readily than manganese in wolframite, scheelite is the more suitable tungsten mineral for this purpose.

Tungsten is also introduced into steel in the form of ferrotungsten; in addition, tungsten powder has been employed in steel making, but its use in the United States has almost ceased.

Production of Ferrotungsten

Ferrotungsten is produced directly from clean concentrates containing at lease 60 percent tungsten trioxide, from tungsten trioxide, or from tungsten powder. In general three methods are employed in the manufacture of ferrotungsten:

1. Electric furnace reduction with or without carbon.
2. Aluminothermic reduction.
3. Crucible reduction with carbon.

The first method is perhaps that used most generally in the United States. Economical production of high-grade ferrotungsten from scheelite, wolframite, and ferberite involves many problems; copper, arsenic, tin, lead, antimony, bismuth, manganese, and sulphur are troublesome; furthermore, specifications for carbon and silicon in the ferrotungsten must be observed.[18] Preparation of reasonably pure tungsten oxide by wet methods and the electric-furnace reduction of this oxide are steps through which a very high-grade product may be obtained, but such procedure can hardly be classed as economical at the present time in this country.

The electric-furnace method for the production of ferrotungsten at Boulder, Colo., has been described by Keeney.[19] By this method ferberite or other

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18/ Becket, Frederick M., The Development of Ferro-Alloys of Tungsten and Vanadium: Chem. and Met. Eng., vol. 30, 1924, p. 391.

19/ Keeney, R. M., The Manufacture of Ferro-Alloys in Colorado: Eng. and Min. Jour., vol. 106, 1918, p. 405.

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tungsten concentrate is reduced with carbon in the form of coke; lime and fluorspar also are added. The crude metal obtained is subsequently refined and decarburized.

Before the electric furnace was introduced in industry (about 1900) ferrotungsten was produced mainly by reducing concentrates or tungstic acid with carbon in crucibles. By this process a charge of concentrates, flux, steel or scrap iron, and coke or charcoal was placed in a clay-lined crucible and heated in a gas-fired furnace.

Ferrotungsten can also be made by reducing tungsten concentrates or tungstic oxide with aluminum in the electric furnace. The oxygen contained in the metals present furnish the oxygen for burning the aluminum. The charge is mixed in a magnesia crucible and ignited by a fuse of sodium or barium peroxide and aluminum powder. The ferrotungsten produced is almost free from carbon but may contain aluminum unless there is a slight excess of ore or tungsten oxide. It will also contain any other reducible metals present in the ore.

Production of Tungsten Trioxide

Several methods for the decomposition of tungsten concentrates into tungstic acid have been suggested or patented; in a general way they may be grouped as follows:

1. Fusion with alkaline carbonates.
2. Digestion with caustic alkalies.
3. Digestion with acids.
4. Fusion with sodium sulphate and coke or similar mixtures.

The first two methods are the most important commercially in the United States.

Pure tungsten cannot be produced by direct smelting from its ores or concentrates, as can the more common metals. Metallic tungsten is produced by a two-stage process involving chemical preparation of tungsten trioxide and subsequent reduction in furnaces. A fairly pure tungsten metal in powdered form results. The high melting point of tungsten, more than any other factor, has forced the industry to use these unique methods.

The fusion method of making tungsten trioxide, as used by the Fansteel Products Co., has been described by Jones.[20/]

The wolframite concentrates are first pulverized and then mixed with Na_2CO_3, using 15 percent more of the latter than the weight of the WO_3 present. This mixture is ground to minus 100-mesh; and a 300-pound charge is fed into a hand-rabbled gas-fired reverberatory furnace, where it is sintered at 800° C. for 2 hours. After sintering the charge is crushed to pea size, and the sodium tungstate is dissolved in water in wooden tanks equipped with wooden

20/ Jones, Chester H., Manufacture of Pure Tungsten Metal: Chem. and Met. Eng., vol. 22, 1920, pp. 9-16.

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stirring paddles. The solution is then filtered, washed and heated to the boiling point in a wooden or stoneware tank by a steam jet, and an excess of $CaCl_2$ solution is added. The charge is transferred to a stoneware vessel, and about 20 gallons of HCl are added to the heated solution. The supernatant liquor is decanted, treated with lime, and reused in the reaction with sodium tungstate. The precipitate is commercial tungstic acid containing 99.53 percent H_2WO_4. This acid is transferred to enamel-steel tanks and purified further by adding about 5 gallons of NH_4OH and enough distilled water to give a 7-percent solution of ammonium paratungstate. It is heated with steam and filtered through a special wooden press with a paper-filtering medium and glass spigots. The paratungstate solution is evaporated to a small bulk in enameled kettles, and the ammonium fumes are condensed for reuse. The solution is then filtered on stoneware suction filters and the white ammonium paratungstate washed with distilled water. The paratungstate is next treated with a 40-percent solution of C.P. nitric acid in steam-jacketed enamel-lined kettles, where it is converted into H_2WO_4. After the tungstic acid is filtered and washed it is purified further by the same steps used in treating the commercial H_2WO_4.

The double-purified tungstic acid is heated in silica crucibles in a gas-fired oven at 1,000° C.; the product averages 99.94 to 99.96 percent WO_3.

The method whereby the concentrates are digested with caustic alkalies is described by Gero and Iredell.[21]

Chinese wolframite concentrate is crushed so that 100 percent will pass through a 100-mesh sieve and 80 percent through a 200-mesh sieve. The pulverized ore is digested at boiling temperature with strong caustic-soda solution until decomposition is complete. The resulting sodium tungstate is decanted off and the insoluble residue washed with water. The strong sodium tungstate solution and the wash waters are combined.

Calcium chloride solution is added to the sodium tungstate solution, forming a white precipitate of calcium tungstate. This precipitate is allowed to settle and washed by decantation until free of soluble salts. The calcium tungstate, is run into an excess of boiling HCl and digested at a temperature near the boiling point.

The tungstic acid formed is allowed to settle and then washed free of soluble impurities. The tungstic acid slurry is dissolved in an excess of ammonium hydroxide, forming ammonium tungstate solution. This solution is neutralized with pure HCl, whereby fine white needles of ammonium paratungstate are precipitated; these are allowed to settle and are washed thoroughly by decantation.

The dried ammonium paratungstate crystals are ignited to volatilize the ammonia and water, leaving pure tungstic oxide containing 99.982 to 99.990 percent WO_3.

21/ Gero, W. B., and Iredell, C. V., Making Pure Tungstic Oxide Involves Many Unusual Plant Problems: Chem. and Met. Eng., vol. 35, 1928, pp. 412-417.

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Acid-leaching methods are used in producing tungsten oxide from tungsten concentrates; such methods are particularly applicable to scheelite, as it is decomposed more readily by heating with concentrated HCl or HNO_3, giving calcium chloride or nitrate and tungstic acid. The filtered crude tungsten oxide is extracted with ammonium and ammonium carbonate solution, forming ammonium tungstate.22/

The ammonium tungstate is crystallized out; on ignition these crystals are decomposed, giving tungstic oxide and ammonia, which may be recovered for further use.

Tungsten ores containing tin have been fused with potassium sulphate in a muffle furnace to produce tungsten oxide.23/ After the sulphate is fused the ore is thrown in the furnace and the mass stirred continually while the temperature is increased until the entire mass is fluid enough to run out of the furnace. The solidified, fused mass is ground and treated with water, which dissolves the soluble sulphates and phosphoric acid and leaves insoluble potassium acid tungstate as a white precipitate. The insoluble residue is dried and treated with a warm solution of ammonium carbonate or cold ammonia water through which carbon dioxide is passed. The potassium acid tungstate dissolves and leaves the silica, cassiterite, and insoluble sulphates. The solution is evaporated to crystallization, which gives ammonium tungstate from which tungstic oxide is made by heating.

Production of Tungsten Powder

Tungsten powder is obtained from the trioxide by several methods the most important of which are:

1. Electric-furnace reduction with hydrogen.
2. Crucible reduction by carbon.

In the first method, purified tungsten trioxide is placed in small nickel boats, which are inserted in electric tube furnaces and heated in a current of hydrogen at 1,200° C. The tungsten forms as a gray powder. The excess hydrogen is recovered for reuse by removing the water from the exit gases.24/

In early metallurgical practice in the United States most of the tungsten powder was produced by reducing the trioxide in crucible furnaces with carbonaceous agents of various kinds. The tungsten powder produced in this way is less pure than that obtained by hydrogen reduction.

Other methods of reducing tungsten trioxide to powder have been patented or tried, such as reduction by carbon in the electric furnace and reduction by aluminum, zinc, or magnesium.

22/ Liddell, Donald M., Handbook of Chemical Engineering: McGraw Hill Book Co., New York, 1922, p. 896.

23/ Gin, G., Memoir on the Methods of Treatment of Simple and Complex Ores of Tungsten: Trans. Electrochem. Soc., vol. 13, 1908, pp. 481-541.

24/ Jones, Chester H., Manufacture of Pure Tungsten Metal: Chem. and Met. Eng., vol. 22, 1920, pp. 9-16.

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Preparation of Ductile Tungsten

Before 1907 tungsten was known as a hard, brittle metal which could not be worked by mechanical means. The search for a method of producing tungsten in ductile form so that it could be drawn into fine wire for electric-lamp filaments disclosed that it lost its crystalline character by heating and working. For this purpose a very pure tungsten powder is required.

In the process of preparing ductile tungsten as described by Jones,[25] the gray tungsten powder obtained by the reduction of the oxide with hydrogen is placed under a hydraulic press and formed into bars averaging about 1 inch square and 8 inches long. These bars are placed between contacts and sintered by an electric current of 2,750 amperes and 220 volts single phase.

The sintered bars are then heated in an atmosphere of hydrogen in specially designed electric furnaces. Each furnace is a refractory alundum tube surrounded by a jacket which forms an annular space about the tube. The hydrogen introduced into this space permeates the walls of the alundum tube and enters the center of the tube where the metal bar is placed. The hydrogen then passes out through the opening through which the bar has been placed and burns in contact with air.

One end of the heated bar is drawn through a swaging machine. The bar is then reversed in the furnace and heated and the drawing operation is repeated. This cycle is continued until the bar is reduced to the required size, either as bar or heavy wire. For the finer wires used in electric lamps the tungsten is heated repeatedly, swaged, and drawn through diamond dies.

In the manufacture of sheet tungsten a swaged bar about 3/8 by 3/4 inch in section is heated in an electric furnace and rolled; the heating and rolling are continued until the bar is brought to a thick strip. As the strip becomes thinner care must be exercised during the heat to prevent excess heat from resintering the metal. By continued heating and rolling the bar is reduced to the required thickness.

Preparation of Cemented Tungsten Carbide

In the preparation of cemented tungsten carbide extremely fine tungsten powder of high purity is required. The tungsten powder is first carburized to produce tungsten carbide, by passing through a furnace containing carbonaceous gas or by heating under hydrogen intimately mixed with pure and finely divided carbon.[26]

The tungsten carbide is then milled in a stainless steel ball mill with powdered cobalt, which coats each particle of tungsten carbide with a thin pellicle of that metal. Cobalt acts as the cementing material. After

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25/ Jones, Chester H., work cited, pp. 13-14.
26/ Comstock, Gregory, Tungsten Carbide - The First Product of a New Metallurgy: Iron Age, vol. 126, 1930, pp. 1381-1383.

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milling, the metals are compacted in a steel die under hydraulic pressure to form billets of the desired shape. These billets are heated in hydrogen at a temperature that permits enough cohesion to prevent breaking while the material is being shaped with a steel tool to the desired form. Final sintering is done in an atmosphere of hydrogen at brilliant white heat. During this last step, cementation takes place; the final product consists of particles of tungsten carbide cemented together with cobalt containing some tungsten and carbon. Except for final grinding and perhaps lapping, where a fine finish and sharp edges are desired, the product is now ready for use.

DOMESTIC TARIFF HISTORY

Before the Tariff Act of 1909, crude tungsten ores and metallic tungsten were exempt from duty under the Tariff Act of 1897. The 1909 act provided the following duties on tungsten:

> Tungsten or wolfram metal, valued at $200 per ton or less, 25 per centum ad valorem; valued at more than $200 per ton, 20 per centum ad valorem. (Par. 184.)
>
> Tungsten-bearing ores of all kinds, 10 per centum ad valorem. (Par. 190.)

Under the Tariff Act of 1913:

> Ferrotungsten***tungsten or wolfram metal***and other alloys used in the manufacture of steel, not specifically provided for, 15 per centum ad valorem. (Par. 102.)
>
> Tungsten-bearing ores of all kinds, free. (Par. 633.)

The Tariff Act of 1922 provided that:

> Tungsten ores or concentrates, 45 cents per pound on the metallic tungsten contained therein***ferrotungsten, metallic tungsten, tungsten powder, tunstic acid, and all other compounds of tungsten, 60 cents per pound on the tungsten contained therein and 25 per centum ad valorem; ferrochromium tungsten, chromium tungsten, chromium cobalt tungsten, tungsten nickel, and all other alloys of tungsten not specially provided for, 60 cents per pound on the tungsten contained therein and 25 per centum ad valorem. (Par. 302.)

The revised tariff, which became effective June 18, 1930, carried the following provisions affecting tungsten:

> ***Scrap steel, hammer scale, roll scale, and mill scale, 75 cents per ton: ***Provided further, That nothing shall be deemed scrap iron or scrap steel except secondhand or waste or refuse iron or steel fit only to be remanufactured; Provided further, That an additional duty*** of 72 cents per pound on the tungsten content in excess of two-tenths of 1 per centum, *** shall be levied, collected, and paid on all the foregoing. (Par. 301.)
>
> Tungsten ore or concentrates, 50 cents per pound on the metallic tungsten contained therein. *** (Par. 302c.)

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Tungsten metal, tungsten carbide, and mixtures or combinations containing tungsten metal or tungsten carbide, all of the foregoing, in lumps, grains, or powder, 60 cents per pound on the tungsten contained therein and 50 per centum ad valorem; tungstic acid, and all other compounds of tungsten, not specially provided for, 60 cents per pound on the tungsten contained therein and 40 per centum ad valorem. (Par. 302g.)

Ferrotungsten, ferrochromium tungsten, chromium tungsten, chromium cobalt tungsten, tungsten nickel, and all other alloys of tungsten not specially provided for, 60 cents per pound on the tungsten contained therein and 25 per centum ad valorem. (Par. 302h.)

Ingots, shot, bars, sheets, wire, or other forms not specially provided for, or scrap, containing more than 50 per centum of tungsten, tungsten carbide, molybdenum, or molybdenum carbide, or combinations thereof: Ingots, shot bars, or scrap, 50 per centum ad valorem; sheets, wire or other forms, 60 per centum ad valorem. (Par. 316b.)

PHYSICAL AND CHEMICAL PROPERTIES OF TUNGSTEN METAL

The uses of tungsten metal depend on its unique physical and chemical properties. Pure tungsten metal does not have the extreme hardness which characterizes its alloys; as measured on the Mohs scale the hardness of the metal ranges from 4.5 to 8, depending on the manner of working. Relatively small quantities of some impurities appreciably affect the properties of the metal. Because of its toughness tungsten is not readily machined. It has the highest melting point (3,350° C.) of all the metals and, with the exception of carbon, the highest melting point of all substances. When worked tungsten becomes elastic and extremely ductile, so that it can be drawn into finer wire than any other metal. After working, the metal attains the highest tensile strength of any known metal, ranging from 490,000 to 610,000 pounds per square inch. As fine wire it retains its rigidity at higher temperatures than any other metal; moreover, it has the lowest vapor pressure. The density of tungsten ranges from 19.3 to 21.4, depending on the mechanical treatment it receives. The boiling point of tungsten is about 5,830° C.

Tungsten forms alloys readily with nickel, cobalt, molybdenum, uranium, chromium, iron, manganese, vanadium, and titanium and less readily with nearly all of the other metals.

Tungsten metal is not affected by oxygen at ordinary temperatures. With carbon or boron in the electric furnace it forms metallic carbides or borides of great hardness. At ordinary temperatures the metal is insoluble in hydrochloric, sulphuric, nitric, or hydrofluoric acids. Aqua regia has no effect except to oxidize the surface of the metal to tungstic oxide. However, in a mixture of hydrofluoric and nitric acids it dissolves rapidly.

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USES OF TUNGSTEN

Steel Alloys

Although tungsten has a great variety of uses its greatest use is as a component of high-speed tool steel. The value of high-speed steel for cutting purposes depends on its ability to retain its hardness when heated to redness. The use of tungsten-steel cutting tools increases the output per man and per machine enormously and results in saving millions of dollars annually. One man and one machine can do as much work with high-speed tungsten steel as five men and five machines could formerly with simple carbon steels.

One tungsten steel containing 3 to 4 percent tungsten is used for finishing cuts on iron and steel.

An important use for high-speed steel is in the manufacture of valves and valve seats for internal combustion engines, particularly airplane engines. These valves sometimes operate at red heat, and as the steel is red-hard at this temperature it gives good results.

High-speed steel is used for drawing dies in the manufacture of certain wires.

Tungsten is used in steel rails. It has been estimated that the life of rails is prolonged 5 years by the addition of 0.3 percent tungsten.

In 1900 tungsten was used for making armor plate at the Krupp Works, Germany, and the Creusot Works, France. It was also used in the manufacture of projectiles to be fired at armor plate. An alloy of 35 percent tungsten and 65 percent steel will make a shell of high penetrating power. Reduction of the caliber of guns is necessarily accompanied by diminution in the weight of projectiles. The projectiles can not exceed a certain length; beyond this limit they would no longer have sufficient stability in their trajectory. Tungsten, by virtue of its high density and hardening properties in alloys, appears desirable in the manufacture of projectiles, but its comparative scarcity precludes its use for that purpose on an extensive scale.

Tungsten has been used in steel for lining cannon, particularly by the Austrian government. Its resistance to erosion and heat increases the life and permits more rapid firing.

Tungsten is also used in steels for hacksaw blades, files, cold chisels, razor and knife blades, stamps, watch springs, strings for musical instruments, phonograph needles, sounding plates of pianos, car springs, electrical resistance wire, drills, rolls for Pilger mills, shear blades for cutting hot steel, armor for submarine cables, telephone conductors, and transformer cores.

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Cemented Tungsten Carbide

Cemented tungsten carbide has created a new metallurgy and opened a new field of alloys for use of the engineer. In the past, some materials which have desirable properties have not found a wide application because of the difficulties encountered in machining with the steels available. These materials can now be machined on a commercial basis with cemented tungsten carbide tools.

Cemented tungsten carbide is offered to the trade at $450 per pound (about $1 per gram).[27] This high price is attributable to the cost of research and the present difficulties in manufacture. Being a high-priced material, it is utilized by inserting tips on steel shanks by copper brazing in an atmosphere of hydrogen or by welding. In spite of the high price, in many applications the user employs it at a distinct advantage over plain carbon-tool steels, which by comparison are as soft as lead.

Cemented tungsten carbide has been used in place of diamonds for drilling rock and can be used in place of the old-time saw teeth for cutting rock. It is also used in gages, blast nozzles, boring and reaming tools, blanking and drawing dies, and similar applications.

Nonferrous Alloys

Numerous alloys containing tungsten in conjunction with most of the metals have been invented, but the cost of the alloy is often out of proportion to its usefulness. In general tungsten in alloys usually gives hardness and greater resistance to oxidation and corrosion.

Perhaps the most widely known nonferrous alloy of tungsten is one of the stellite alloys containing about 75 percent cobalt, 20 percent chromium, and 5 percent tungsten; other elements sometimes are added. This alloy is one of the chief competitors of high-speed tool steel. It is also used in cutlery, because it takes a high polish and is unaffected by fruit acids.

Aluminum hardened with a small amount of tungsten, called partinium, is both light and strong and is used in France for automobile construction.

Duralumin is an alloy of aluminum hardened with 2 or 3 percent tungsten and has a tensil strength of 32,000 pounds per square inch. An alloy of aluminum, copper, and tungsten is used for propeller blades. Another aluminum alloy containing 10 percent tungsten has been patented for type metal.

An alloy containing 2 to 10 percent cobalt and the balance tungsten has been patented in Germany for breeches for naval guns.

Sideraphite is an alloy containing iron, nickel, copper, aluminum, and tungsten; it resembles silver in appearance and is ductile, malleable, and resistant to corrosion.

27/ Jeffries, Zay, The Present Status of Cemented Tungsten Carbide Tools and Dies: Metals and Alloys, November 1929, p. 223.

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Tungsten-nickel containing varying proportions of these two elements has been used for electric-lamp filaments.

Platinoid, an alloy containing copper, zinc, nickel, and tungsten, has been used as electrical resistance wire in filament lamps. It has a coefficient of expansion similar to that of glass.

Before the introduction of ductile tungsten many patents were issued for alloys of tungsten containing small amounts of thorium, or nickel, to be used in the manufacture of electric-lamp filaments. The addition of these metals made the tungsten ductile..

The General Electric Co. has developed a copper-tungsten electrode for welding, under the trade name of Elkonite, which does not anneal at red heat and is used for special applications where copper alone will fail.

Tungsten alloys have been suggested for jewelry. An alloy containing 75 percent gold, 10 to 15 percent tungsten, and 15 to 10 percent nickel is easily rolled and hammered and takes a fine polish. A similar alloy in which silver replaces the gold is easily polished and resists oxidation. An alloy containing 20 to 60 percent tungsten and 80 to 40 percent platinum has been patented for jewelry, electrical contacts, etc.

Tungsten-molybdenum alloys of varying composition are used as substitutes for platinum in dentistry.

A tungsten-nickel alloy carrying 75 percent tungsten and 25 percent nickel is used in hardening steel.

Other nonferrous alloys containing tungsten have been invented for, surgical instruments, electrical contact points, jewelry, pen points, high-speed bearing metals, safe and vault walls, filament supports for radio tubes, and various uses where resistance to acid liquids or vapors is desired.

Metallic Tungsten

The use of metallic tungsten for electric-lamp filaments is well known, yet this use consumes only a small part of the tungsten produced. Between 3 and 4 tons of tungsten concentrates containing 60 percent tungsten trioxide will make the filaments for 100,000,000 lamps. In the transition from the carbon to the tungsten filament numerous metals have been tried, but only a few were moderately successful. A metal suitable for incandescent lamp filaments must have a high melting point, be ductile, and possess a low vapor tension under working conditions, while its radiation must be highly selective. Waidner and Burgess[28] have shown that the light emitted by an incandescent metal varies as the twelve power of the temperature, and the energy required varies as the fifth power of the temperature. An increase in the working temperature is therefore very important.

28/ Waidner, C. W., and Burgess, G. K., U. S. Bureau of Standards, vol. 2, 1907, p. 319.

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According to Zay Jeffries:[29]

> In the present state of the electric-incandescent-lamp art the average efficiency during the life of a tungsten-filament lamp is 4 1/2 times that of the carbon-filament lamp. Leaving out of consideration miniature lamps, there are consumed annually in the United States alone over 15 billions of kilowatt-hours of electrical energy for illumination at a cost to the consumer of approximately $800,000,000. If the same level of illumination were maintained in the United States by the use of carbon lamps, assuming the same average cost of electrical energy to the consumer, an additional expenditure of about $2,900,000,000 would have to be made. Incidentally this amount of money would more than buy all the pig iron and nonferrous metals produced in the United States in a year. It is of course obvious that if we were still using carbon lamps we would not enjoy the present level of illumination. If we had, however the present level of illumination with carbon lamps, and assuming that no other material except tungsten to be available to replace carbon, we could afford to pay about $330,000 per pound for tungsten and still obtain our light at the same cost. The actual cost of tungsten at the present time, in the ore, is less than a dollar a pound. This is only one illustration of the general proposition that the cost of a metal to the consumer is a function of its concentration in the earth's crust and its ease of recovery rather than its value to industry.

Inasmuch as drawn tungsten wire has a high tensile strength and can be drawn into wire having a diameter of 0.0004 inch it has been used for galvanometer suspension, cross hairs in telescopes, radio tubes, rectifying valves, X-ray tubes, and surgical wire, replacing gold and silver wires. Tungsten wire is an excellent material for wiring electric furnaces on account of the high temperature maintained.

Tungsten is used for making vacuum seals through special glass with a coefficient of expansion approximating that of tungsten.

Tungsten contact points are used in spark coils, voltage regulators, telegraph keys, and similar devices in place of platinum-iridium formerly used. The cost of platinum for such uses is much higher than the cost of tungsten. Sheet tungsten has been found to be a very efficient metal for the construction of amplifiers in wireless apparatus.

Tungsten electrodes are used in certain electrochemical processes where resistance to corrosion is desired.

Tungsten-molybdenum thermocouples are used for measuring high temperatures as the electromotive force increases with an increase in temperature.

Tungsten gauze resists acids and alkalies; it is used in separating liquids from solids where corrosion is a factor. It has also been used in some of Cottrell apparatus for the electrostatic precipitation of fumes.

29/ Jeffries, Zay, Engineering and Science in the Metal Industry: Mech. Eng., vol. 48, 1926, p. 8.

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Tungsten crucibles have been used in vacuum furnaces or in furnaces filled with inert gases. Laboratory apparatus has been made from wrought tungsten where resistance to corrosion is desired.

Since tungsten has high specific gravity, high heat conductivity, high melting point, and low vapor pressure tungsten buttons brazed to copper have been used as anticathodes in Roentgen (X-ray) tubes.

Recently tungsten was deposited from an alkaline solution by electrolysis;30/ its use in electroplating may open a wide field. The tungsten deposited from aqueous alkaline solutions is smooth, hard, and coherent and has a high luster. Like chromium, it needs no polishing if the plated articles were previously polished. Because of its acid-resisting properties tungsten is useful as a coating for other metals.

Tungsten has also been used as a catalyst in the production of ammonia from nitrogen of the air.

Chemical Compounds

Sodium tungstate is used as a mordant in dyeing, for rendering cloth noninflammable, for weighting fabrics such as silk, in painting, for decolorizing acetic acid and acetates prepared from pyroligneous acid, and as a decorticator in preparing raw fibers for manufacturing.

Fluorescent cadmium tungstate is used in making fluorescent screens for visual observation in X-ray practice; considerable fluorescent calcium tungstate is employed in making intensifying screens for X-ray photography.

Lead, zinc, and barium tungstates are used as substitutes for white lead.

The pure oxide is used as an oil and water color and when converted into blue oxide is used as a pigment. The oxide also is employed in ceramics to produce various shades of yellow in glass and porcelain.

The so-called tungsten bronzes are made by fusing an alkali tungstate and pure tin. Various shades of red, yellow, or blue are thus formed and used for decorative purposes.

Yellow, blue, green, pink, and gold tungsten salts are employed in the manufacture of stained papers.

MARKETING TUNGSTEN CONCENTRATES

The value of tungsten concentrates is determined by the tungsten content invariably expressed in terms of tungsten trioxide.

30/ Fink, Colin G. and Jones, Frank L., The Electrodeposition of Tungsten from Aqueous Solutions: Trans. Electrochem. Soc., vol. 59, 1931, 23 pp. (preprint).

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The term "unit", when used in stating the price of tungsten concentrates, is synonymous with percent of WO_3. Marketing tungsten concentrates on the unit basis is prescribed by custom. A unit representing 1 percent tungsten trioxide in 1 ton of concentrates may be 20, 22.4, or 22.04 pounds, depending on the size of the ton (short, long, or metric). In the United States prices are quoted in short-ton units, whereas in the British Empire they are quoted in long-ton units. France and Germany employ the metric-ton unit.

There is no standard for setting a price on tungsten concentrates; beyond a general quotation on concentrates containing 60 percent WO_3 selling is subject largely to supply and demand bidding. In general, tungsten concentrates must contain at least 60 percent (60 units per short ton) tungsten trioxide to be salable; moreover, they must be relatively free from such impurities as antimony, arsenic, bismuth, copper, lead, manganese, nickel, phosphorus, tin, zinc, and sulphur. All buyers do not object to the same impurities in the concentrates; and sometimes in a brisk market off-grade ores can be sold, but at a discount. Ores from different districts often are quoted at different prices, and no definite scale of premiums and penalties has been fixed. The grade of concentrates desired by consumers depends on the method of converting and the use to which the tungsten metal or compound is to be put. Tungsten concentrates used in the manufacture of alloy steels and for conversion into metal are subject to rigid requirements as to impurities. The following quality guarantee, required by some manufacturers, illustrates in a general way the requirements:

	Percent
Tungsten trioxide	65-70
Tin (maximum)	Trace
Arsenic (maximum)	0.035
Antimony (maximum)	.035
Bismuth (maximum)	.035
Copper (maximum)	.05
Sulphur (maximum)	.75
Phosphorus	.05

If requirements as to deleterious elements were not rigid the quality of the finished alloys might be impaired or even destroyed by their presence.

Production of tungsten concentrates in the United States is characterized by many actual and potential producers, only a few of whom are well-financed. There is no tendency toward an integrative policy whereby the consumer is also the producer; only one tungsten-mining company at present is affiliated with consuming interests.

Since tungsten ores are not exploited on a large scale the market is unstable. Moreover, there are no effective organizations of buyers or sellers, so that domestic producers must deal either through brokers or direct with consumers by private negotiations.

Tungsten concentrates usually are sold in carload lots (35 tons), and if the market is heavy smaller lots are difficult to sell.

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Concentrates are sold on a custom assayer's certificate of weighing, sampling, and analysis. No legal or trade rule requires buyers or sellers to bear this cost; generally they share it by mutual agreement.

Before 1918 ferberite was preferred to scheelite, but changes in the practice of using tungsten concentrates created a larger demand for the latter. For reduction of tungsten minerals to metal or ferrotungsten high-grade concentrates are required because the capacity of the electric furnace in which they are reduced is limited. From the viewpoint of metal content in the economic tungsten minerals scheelite contains the most tungsten. Taking scheelite as 100 the tungsten content of the four principal tungsten minerals is as follows:

Scheelite	100
Ferberite	98.5
Wolframite	96.5
Hübnerite	90.0

Marketing of tungsten concentrates has been hampered in the past by a lack of standard requirements, the wide territory over which the deposits are distributed, and lack of centralization in buying or selling.

STRATEGIC IMPORTANCE OF TUNGSTEN AS A WAR MINERAL

Due to the unique role of tungsten in our economic structure it is one of the pivotal war minerals. Since the comparative efficiency of tungsten-alloy cutting tools is 3 to 5 times that of carbon steel the large amounts of lathe-turned, drilled, or planed steel required for armaments in the World War could hardly have been produced by the use of carbon-steel tools. Consequently tungsten is a vital necessity to the welfare of the country in a time of national emergency.

Germany was the only nation that properly appraised the importance of tungsten as a strategic war mineral before the World War. At that time she virtually monopolized the production of ferrotungsten; tungsten concentrates produced in various parts of the world were shipped to Germany for fabrication into high-speed steel. With characteristic thoroughness Germany developed tungsten mines in various parts of the world, including the United States, Peru, Bolivia, Argentina, and Burma. The position of the ferrotungsten industry before the war was one of the most striking examples of Germany's industrial domination of a raw material she herself almost wholly lacks. In 1913 Germany produced only 1 percent of the world output of tungsten ore yet she controlled 60 percent of it.[31/] Great Britain through her possessions produced 37 percent of the world output, yet she depended on Germany not only for ferrotungsten but also for her tungsten-steel tools, which even though purchased through English firms were derived from German manufacture.

31/ Bliss, Eleanora F., Some Problems of Readjustment of Mineral Supplies as Indicated in Recent Foreign Literature: Econ. Geol., vol. 14, 1919, p. 166.

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In 1913 France produced 12 percent of the world output and in addition controlled the production of a mine in Portugal and held an interest in the Bolivian enterprises. Owing to her development of water power she had a pre-war production of ferrotungsten, although she was not in position to compete with the German output of ferro-alloys or high-speed tools.

In the United States before the war only a few technical men realized the importance of tungsten as an essential ingredient in the manufacture of tool steel and as a cornerstone of mass production of munitions. Tungsten was unknown to the man in the street; the major part of our tool-steel requirements was imported to meet industrial needs.

When the war broke out the manufacturers of high-speed tool steel in England found themselves without an adequate supply of tungsten, owing to German control. Establishment of the tungsten industry was of paramount importance; following Government inquiry a committee of leading English steel manufacturers was formed, and 31 firms took shares in the company organized, the High-Speed Steel Alloys (Ltd.). In September 1915 the British Government assumed control of the production of tungsten ores within the Empire and apportioned them among the makers of ferrotungsten.

This British embargo on tungsten was reflected in the United States, when munitions manufacturers realized that tungsten steel was unobtainable. The steel manufacturers sent men scurrying over the world to purchase ores and concentrates; domestic search for additional tungsten deposits was so stimulated that many new deposits were found. Although the domestic production of tungsten concentrates jumped from 2,332 tons in 1915 to 6,144 tons in 1917 the supply was inadequate to meet the emergency requirements.

In order that the domestic supply of tungsten shall be adequate in time of war the following suggestions have been proposed:

1. Substitute other metals for tungsten.

2. Cessation of domestic production and reservation of the deposits solely for emergency use.

3. Accumulation and maintenance of a reserve supply of tungsten concentrates.

4. Stimulation of domestic production by tariff protection.

In discussing substitutes for tungsten peace-time requirements of comparative costs need not be considered; war conditions impose quantity and quality. Assuming that the resources of tungsten ores in the United States are inadequate for war purposes, the number of substitutes available are limited. The principal substitute suggested and tried is molybdenum, but it was not as satisfactory as tungsten in high-speed steel. Taylor[32] found that molybdenum

32/ Taylor, F. W., On the Art of Cutting Metals: Trans. Am. Chem. Soc., vol. 28, 1906, pp. 31-35.

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steels for cutting purposes caused irregular performance; that steels of nearly the same composition and receiving the same treatment varied considerably in cutting speeds. More extensive research on the metallurgy of molybdenum has overcome these difficulties. Ritchie[33] has announced that molybdenum can be substituted in whole or in part for tungsten in high-speed tools and that all difficulties in the manufacture of molybdenum high-speed tools can be overcome.

If molybdenum can be substituted for tungsten in high-speed steels it must rank as a competitor of tungsten under normal industrial conditions to be available quickly in time of a crisis, since war-time applications of the metals are largely an extension and expansion of their peace-time applications. In general, the major difficulty in substituting other metals for war minerals is the fact that the metal for which substitution is to be made usually is the one that accomplishes the desired results. Introduction of molybdenum for tungsten during a crisis would involve a change in technic which might result in the loss of considerable time. Molybdenum eventually may displace tungsten but the extent of its use in high-speed steel under normal working conditions cannot be predicted.

Other alloys containing zirconium, uranium, vanadium, and tantalum have been developed as substitutes for tungsten in high-speed steels, but the comparative scarcity and cost of these metals will no doubt prevent their extensive application.

Substitutes for cemented tungsten carbide cutting tools are possible but as yet have not been developed to the same extent as tungsten. The other hard metal carbides are titanium, zirconium, thorium, vanadium, niobium, tantalum, chromium, molybdenum, and uranium. As this new branch of metallurgy develops one of these hard-metal carbides may be found to be a commercial competitor of tungsten.

It has been proposed that peace-time demand for tungsten should be derived from foreign sources and thus conserve domestic resources for a national emergency. Inasmuch as all extraction of ore is depletion and cannot be replaced this plan would be advantageous if domestic resources were small and the supply immediately available during a crisis. Only through Government control could this plan be carried out. Industrial development in the United States, however, has been intrusted to the control exerted by the natural law of supply and demand working under free competition. Although plausible in theory, Government ownership of the tungsten resources is not likely to appeal to the American people.

If domestic resources of tungsten ores are to act as a safeguard in an emergency they must be available when the emergency arises. Even though the deposits are conserved their availability cannot be assured unless the time-consuming mine and process development and plant erection have reached the production point before the emergency arrives. Economically such a course is impracticable, as the very essence of a program of preparedness is to obviate

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33/ Ritchie, S. B., Molybdenum in High-Speed Steel: Army Ordnance, vol. 11, July-August 1930, pp. 12-19.

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all delays. Then, too, solicitude for the welfare of the future can be carried to extremes, inasmuch as there is no assurance that present technic in the production of tungsten products will be permanent.

Accumulation and maintenance of a stock-pile reserve of tungsten concentrates for emergency use have so far been contrary to American policy. The size of the stock pile would depend on the requirements of the essential industries using the raw material and the length of time imports would be restricted or cut off.

Whether or not the tungsten industry should be protected by tariff is a moot question. Without tariff protection the mining of tungsten ores in this country could not survive, as was demonstrated from 1918 to 1923, when imports of tungsten ores brought the domestic production to a standstill. The opponents of a Government subsidy in the form of a tariff base their opposition largely on the supposition that domestic resources of this metal are too limited to justify a duty and should be conserved for national emergency. Our tungsten resources are larger than is generally supposed. Many low-grade deposits of tungsten ores have been discovered in this country within the last 15 years, and only about 25 percent of these have been prospected. Further development of these deposits probably will disclose important new discoveries and extensions to the known deposits, as judged by past history of the mining industry.

In the final analysis the problem resolves to the question of the insurance premium the country is willing to pay to reduce the risk of being wholly dependent on foreign countries for tungsten needs in time of national emergency.

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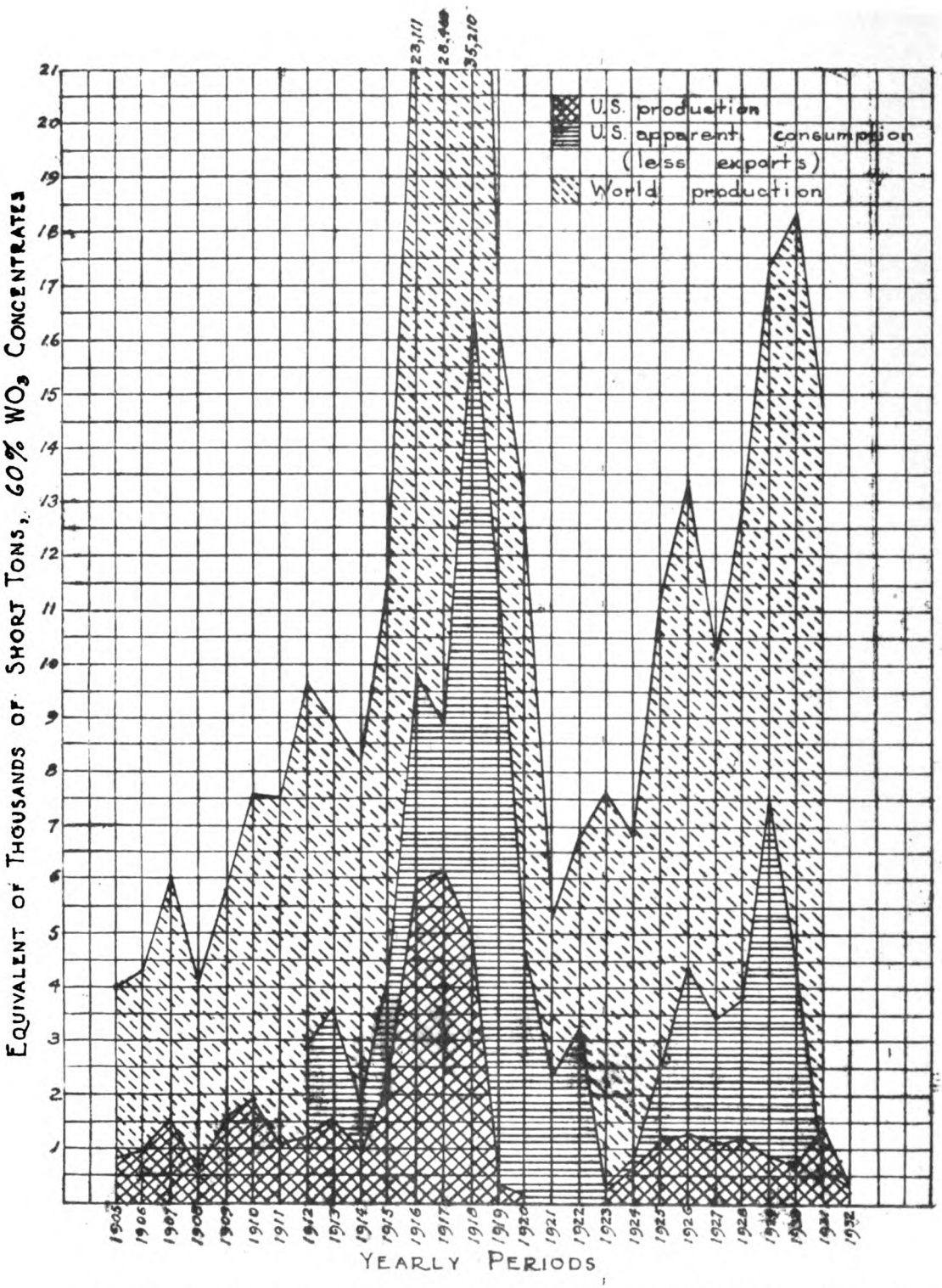

Figure 1.– World production and production and apparent consumption in the United States of tungsten, 1905–32, in short tons containing 60 percent WO_3.

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